

Large Extra Dimensions and Neutrino Oscillations

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Abstract. We consider a model where right-handed neutrinos propagate in a large compactified extra dimension, engendering Kaluza-Klein (KK) modes, while the standard model particles are restricted to the usual 4-dimensional brane. A mass term mixes the KK modes with the standard left-handed neutrinos, opening the possibility of change the 3 generation mixing pattern. We derive bounds on the maximum size of the extra dimension from neutrino oscillation experiments. We show that this model provides a possible explanation for the deficit of ν_e in Ga solar neutrino calibration experiments and of the $\bar{\nu}_e$ in short baseline reactor experiments. *Contribution to NUFAC 11, XIIIth International Workshop on Neutrino Factories, Super beams and Beta beams, 1-6 August 2011, CERN and University of Geneva* (Submitted to IOP conference series)

1. Introduction

Our purpose is to study a large extra dimension (LED) scenario [1] where right (left) handed neutrinos (antineutrinos), i.e., standard model singlet fermions, can propagate in the $1+3+\delta$ -dimensional spacetime, while all the other Standard Model (SM) fields are limited to the $1+3$ dimensional brane. As discussed in Refs. [2, 3, 4, 5, 6], the neutrino masses arise from the Yukawa coupling between the standard left-handed neutrino and the singlet fermions in the $1+3$ dimensional brane. Although this Yukawa coupling naturally explains the smallness of neutrino masses via a volume suppression, it also induces mixing among the standard neutrinos and the KK modes that arise from the singlet fermions after dimensional reduction [7]. Hence, the effect of LED in neutrino oscillations could be probed by terrestrial neutrino experiments. There are plenty data from solar, atmospheric and terrestrial neutrino experiments which can be very well described with the standard three flavor oscillation scheme (see [8] and references therein). Being so, LED, if present, is expected to contribute at the most as a subdominant effect on top of the usual oscillation pattern. Nevertheless, a few mild deviations from that scheme remain.

First, the LSND experiment [9] has observed an unexpected excess of $\bar{\nu}_e$ events in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ mode, which is also supported by more recent MiniBOONE data [10]. Moreover, the GALLEX [11] and SAGE [12] experiments, designed to calibrate gallium radiochemical solar neutrino detectors, observed a smaller than expected ν_e flux originated from ^{51}Cr (GALLEX and SAGE), and ^{37}Ar (SAGE only). The mean value of the ratios of the measured over predicted rates is 0.86 ± 0.05 , comprising a 2.7σ deviation [13], which is the so-called *gallium anomaly*. Finally, a recent re-evaluation of the reactor $\bar{\nu}_e$ flux [14, 15] resulted in an increase in the flux

of 3.5%. Although the impact on the results of long baseline experiments such as KamLAND is negligible, the new flux calculations induce an average deficit of 5.7% in the observed event rates for short baseline (< 100 m) reactor neutrino experiments. This constitute a 98.6 % CL deviation from unity and has been referred to as the *reactor antineutrino anomaly* [16].

In this work, we will derive bounds on the size of the largest extra dimension from neutrino oscillation experiments and show that the discussed anomalies can spring from a LED model.

2. Neutrino Oscillations with a Large Extra Dimension

The LED model considered here is the one described in Refs. [7, 17]. In this scheme, the SM fields are confined to the 1+3-dimensional brane and three SM singlet fermion field can propagate in the higher dimensional bulk with at least two compactified flat extra dimensions. Let us say that one of these extra dimensions is compactified on a circle of radius a and, for simplicity, is much larger than the others, so that a 5-dimensional treatment is a good approximation. The 3 bulk fermions have Yukawa couplings with the SM Higgs and the brane neutrinos ultimately leading to flavor oscillations driven by Dirac masses, m_i ($i=1,2$ and 3), and KK masses m_n^{KK} ($n = 1, 2, \dots$), and mixings among active species and sterile modes. In this case the survival probability $\nu_\alpha \rightarrow \nu_\alpha$ ($\alpha = e, \mu, \tau$) in vacuum, which holds also for antineutrinos, can be approximated by [7, 17, 18]

$$P(\nu_\alpha \rightarrow \nu_\alpha; L, E) = |\mathcal{A}_{\nu_\alpha \rightarrow \nu_\alpha}(L, E)|^2, \quad \text{with} \quad \mathcal{A}_{\nu_\alpha \rightarrow \nu_\alpha}(L, E) = \sum_{i=1}^3 |U_{\alpha i}|^2 A_i, \quad (1)$$

where A_i is given by, assuming $m_i a \ll 1$ and ignoring the terms of order $(m_i a)^3$ and higher in the amplitude as well as $(m_i a)^2$ and higher in the phase,

$$A_i \approx (1 - \frac{\pi^2}{6} m_i^2 a^2)^2 \exp\left(i \frac{m_i^2 L}{2E}\right) + \sum_{n=1}^{\infty} 2 \left(\frac{m_i}{m_n^{\text{KK}}}\right)^2 \exp\left[i \frac{(2m_i^2 + m_n^{\text{KK}2})L}{2E}\right]. \quad (2)$$

Here $U_{\alpha i}$ are the elements of the usual Maki-Sakata-Nakagawa neutrino mixing matrix (we use the standard parameterization found in Ref. [8]), E is the neutrino energy, L is the baseline distance, $m_n^{\text{KK}} = n/a$ is the mass of the n -th KK mode.

As can be seen, the probability depends on the absolute neutrino masses, hence the behavior is different for normal mass hierarchy (NH), where $m_3 > m_2 > m_1 = m_0$, and inverted mass hierarchy (IH), where $m_2 > m_1 > m_3 = m_0$. Clearly, as m_0 increases the differences between the hierarchies fade away and the masses become degenerate. Thus, in this model, neutrino oscillations will be sensitive to the standard oscillation parameters, the size of the extra dimension, and the mass of the lightest neutrino. In fig. 1 we show illustrative oscillation probabilities. For a discussion about the oscillation behavior, see Refs. [7, 18].

We analyzed what region in the $a - m_0$ plane can be excluded by the latest data from CHOOZ [19], KamLAND [20], and MINOS [21] $\nu_\mu \rightarrow \nu_\mu$, for both hierarchies. This was calculated at 90% (99%) CL, by imposing $\chi^2 > \chi_{\text{min}}^2 + 4.61$ (9.21). All parameters were varied freely. The combined exclusion is shown in fig. 2. See Ref. [7] for details.

3. An Interpretation for the Gallium and Reactor Anomalies

Now we address the question: *Can the gallium and reactor anomalies be due to this large extra dimensions model?* To answer that, let us comment first on the gallium anomaly. The radiochemical solar neutrino experiments GALLEX and SAGE have been calibrated with monoenergetic ν_e 's from intense radioactive sources, which are captured by the reaction,

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-. \quad (3)$$

As sources, the GALLEX collaboration used ${}^{51}\text{Cr}$, publishing two measurements [11], while the SAGE collaboration used both ${}^{51}\text{Cr}$ and ${}^{37}\text{Ar}$ [12]. The ratio of the measured ${}^{71}\text{Ge}$ event rate

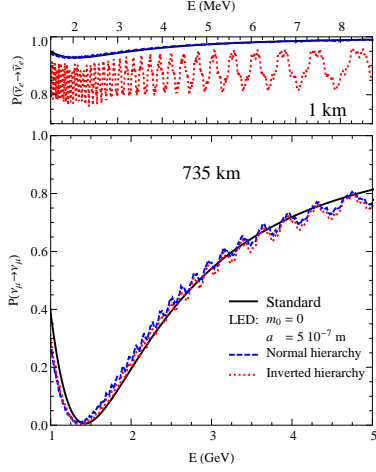


Figure 1. Illustrative oscillation probabilities. See legend in figure for details.

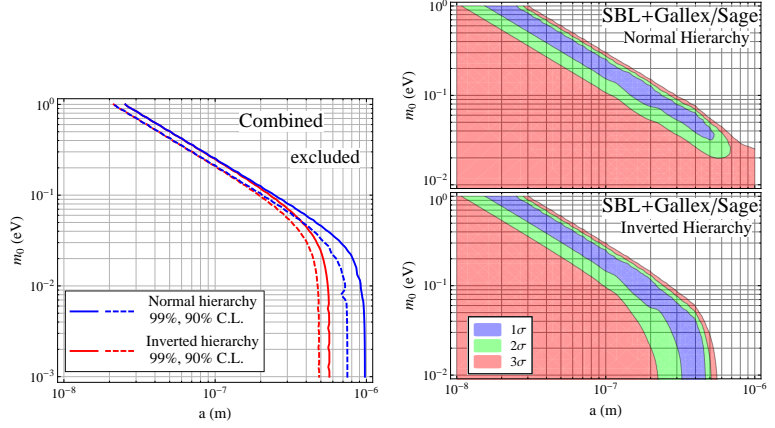


Figure 2. Left: Excluded region in the $a - m_0$ plane by the combined CHOOZ, KamLAND, and MINOS $\nu_\mu \rightarrow \nu_\mu$ as indicated. Right: Allowed region in the $a - m_0$ plane by the combined data set from GALLEX, SAGE and short baseline reactor experiments for each hierarchy as indicated.

over the predicted one (using the cross section estimated in Ref. [22]) are, including 1σ errors, for GALLEX [11] (R^G) and SAGE [12] (R^S).

$$\begin{aligned} R_{Cr1}^G &= 0.95 \pm 0.11 \quad , \quad R_{Cr}^S = 0.95 \pm 0.12, \\ R_{Cr2}^G &= 0.81 \pm 0.11 \quad , \quad R_{Ar}^S = 0.79 \pm 0.09. \end{aligned}$$

We can see that all the ratios are below unity. Accordingly to the analysis in Ref. [13, 23] this represents a 2.7σ deviation from the expected value. We performed a similar analysis (see Ref. [18] for details).

Now, let us discuss briefly the second anomaly, namely the reactor antineutrino anomaly. The reactor antineutrino fluxes have been reevaluated [14, 15], which lead to a 5.7% decrease in the number of $\bar{\nu}_e$ observed and theoretically predicted for all short baseline reactor experiments [16].

We have simulated 19 reactor experiments with baseline shorter than 100 m [24]. Our simulation follows closely the one described in Ref. [16] (for details see Ref. [18]). To obtain the theoretical rates with LED, we used the experimental results available in [24] and the parameterization given in [16] to calculate the expected reactor fluxes.

We have fitted the two gallium calibration experiments described together with the above short baseline reactor experiments using the LED scenario discussed in Section 2, thus obtaining the allowed regions in the $m_0 - a$ plane, for both normal and inverted hierarchies, as shown in fig. 2. We found that the combined data favor the nonzero value of the large extra dimension, 2.9σ away from $a = 0$. These regions quite compatible with the limits obtained in Section 2 coming from other oscillation experiments. The allowed region for explaining the anomalies overlaps scarcely with those excluded by CHOOZ, KamLAND and MINOS.

4. Conclusions

We investigated a large flat extra dimensions model where the SM fields are confined to the 4-dimensional brane while three SM singlet fermion fields can propagate in the bulk. These fields couple to the active neutrino thru a Yukawa term. This generates small neutrino masses,

but also changes the oscillation pattern. We have shown that terrestrial neutrino oscillation experiments can set sub-micrometer bounds on the size of the largest extra dimension.

We also show that the gallium and reactor antineutrino anomaly can be explained by such a model. In this case, the observed deficit of neutrinos is due to the oscillation between active neutrinos and sterile KK modes coming from the SM singlet fermions. While the future MINOS and Double CHOOZ data can improve somewhat the limits in the small m_0 parameter region [25], it seems not easy to exclude or confirm the LED solution discussed in this work.

Finally, we note that the excesses observed in the LSND and MiniBOONE experiments can not be explained by this simple model. Although considering two extra dimensions of different size could, in principle, enhance short baseline $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, naively there is no source of CP violation. An explanation for LSND/MiniBOONE, gallium and reactor anomalies by some extension of the model discussed here could be an interesting subject for further studies.

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